Effects of Galaxy Interaction on the Tully-Fisher Relation:

CO vs HI Linewidths

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Abstract. We investigate effects of galaxy-galaxy interaction on the Tully-Fisher relation. The HI linewidth in interacting galaxies is significantly broader than the CO linewidth, and the HI to CO linewidth ratio is proportional to the strength of interaction. This provides different distances to galaxies measured by the Tully-Fisher relation with the CO and HI linewidths. Distances derived from the HI linewidths are 62% larger than those derived from the CO linewidths for strongly interacting galaxies, and 25% larger for weakly interacting galaxies. We argue that the CO-line Tully-Fisher relation will be more reliable to measure the distances of interacting galaxies as well as galaxies in rich clusters.

Key words: distance scale – Galaxies: distances and redshifts – Galaxies: interactions – Galaxies: general – Galaxies: ISM – Radio lines: galaxies

1. Introduction

The HI Tully-Fisher relation has been the most successful and widely applied tool to measure distances to galaxies (e.g., Tully & Fisher 1977; Aaronson et al. 1986; Pierce & Tully 1988). CO linewidth has been also used in the Tully-Fisher relation instead of HI linewidth. HI linewidth almost coincides with CO linewidth for galaxies in the Coma cluster and other nearby clusters (Dickey & Kazes 1992), for field galaxies (Sofue 1992; Schöniger & Sofue 1994) and for Virgo cluster galaxies (Schöniger & Sofue 1997).

Because the beamsize of CO observations is much sharper than that for HI, we are able to resolve individual galaxies at higher redshift, and avoid contamination by other galaxies in one beam for CO observations. Observations for the CO-line Tully-Fisher relation have been performed using the Nobeyama Radio Observatory (NRO)

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45-m telescope (HPBW = 15"), and CO linewidths have been obtained for galaxies at redshift $cz \sim 29{,}000$ km s^{-1} (Sofue et al. 1996), at which the CO beamsize is still small enough to distinguish galaxies.

HI gas extends far from the center of galaxies beyond the optical radius, while it is deficient in the central region (Bosma 1981). On the other hand, the molecular gas is known to be more concentrated in a better correlation with the optical disk (Young & Scoville, 1982). Since the atomic and molecular gases in galactic disk are distributed separately in radius (Sofue et al.1995; Honma et al.1995), the HI linewidths may be more strongly disturbed by galaxy-galaxy interaction, which is inevitable in rich clusters of galaxies and at high redshifts. Interacting galaxies are generally excluded from a sample of nearby galaxies for the Tully-Fisher relation. However, when we measure distances to farther galaxies, we may overlook features of interaction and overestimate the distances.

In this paper we examine the correlation between CO and HI linewidths of nearby galaxies and discuss the Tully-Fisher relation for interacting galaxies.

2. Data and Sample Selection

In this study the data of CO linewidths are taken from Young et al. (1995), who observed the ^{12}CO $(J = 1 - 0)$ emission line of 300 field galaxies using the 14-m telescope of the Five College Radio Astronomy Observatory (FCRAO) (HPBW = 45"). Among them the CO emission was detected at multiple positions for 103 galaxies. We excluded the following galaxies from our analysis; (1) galaxies for which we could not obtain linewidths due to weak or strange position-velocity diagrams, (2) face-on galaxies $(i < 30°)$ in order to minimize the effect of inner velocity dispersion. As the result of these selection we selected 60 galaxies. We classified these galaxies into 17 interacting galaxies and 43 isolated galaxies. Then we classified the interacting galaxies into three subclasses using the interaction class (hereafter IAC) defined by Dahari (1985). Although the Dahari's IAC is classified into 6 groups based

on features of interaction, we classified them into three classes due to the small sample. Our classification based on Dahari's IAC is as follows;

(1) weakly interacting galaxies (hereafter WIG, Dahari's IAC = 2,3),
(2) strongly interacting galaxies (hereafter SIG, Dahari's IAC = 4,5),
(3) mergers (Dahari's IAC = 6).

According to Dahari's classification, IAC = 1 stands for isolated galaxies. The classification for individual galaxies based on Dahari's method is described in Table 3a and 3b, as well as Column 9 in Table 1. The galaxies which Dahari classified are marked with asterisks.

The CO linewidths are obtained from position-velocity diagrams in the literature (Young et al. 1995). The HI linewidth and inclination of galaxies are taken from Huchtmeier & Richter (1989). Among HI data in the catalog, we selected the data observed at Arecibo 1000-ft, Effelsberg 100-m, NRAO Green Bank 300-ft, Jodrell Bank 250-ft and Parks 64-m telescopes in order to keep the quality of data set.

Linewidths are defined as the full width at 20% of maximum intensity of the global profile. In order to correct for an inclination effect, we adjust to an edge-on orientation by: $W_i = W/\sin i$, where W is the observed linewidth, i is the inclination and W_i is the linewidth corrected for the inclination. Total magnitude, the Galactic and internal extinction corrections and radial velocity corrected to the Galactic Standard of Rest are taken from the Third Reference Catalog of Bright Galaxies(RC3) (de Vaucouleurs et al. 1991).

3. Results

Figure 1 shows a plot of the CO linewidths ($W_{i\,CO}$) versus the HI linewidths ($W_{i\,HI}$) for 17 interacting galaxies and 43 isolated galaxies. The CO and HI linewidths are corrected for the inclination. The CO and HI linewidths approximately coincide with each other for most of isolated galaxies (open circles). On the other hand, in most cases of interacting galaxies (filled symbols), the HI linewidths are clearly broader than those of CO.

Among the interacting galaxies, the differences between the CO and HI line widths in the SIG (filled squares) are larger than in the WIG (filled circles). Table 1 shows the number of galaxies, mean value and standard deviation of the ratio for each class. Here we excluded three galaxies which have small linewidth less than 200 km s^{-1} , namely NGC 598, NGC 3893 and NGC 2976, from the statistics, because errors for small linewidth would amplify the linewidth ratio. The sample of mergers is small so that we cannot discuss their statistics.

Figure 2 shows histograms of W_{HI}/W_{CO} for isolated galaxies, weakly and strongly interacting galaxies. The interacting galaxies have obviously larger values of the ratio

Fig. 1. The CO linewidths versus the HI linewidths corrected for inclination. Isolated galaxies are marked by open circles. Interacting galaxies are marked by filled symbols; mergers by filled triangles, SIG by filled squares, and WIG by filled circles. The subclasses of the interacting galaxies are explained in Section 2.

than the isolated galaxies. The ratio W_{HI}/W_{CO} is proportional to strength of the interaction. This trend is caused by the tidal force of the galaxy - galaxy interaction. The CO gas is tightly confined to the luminous stellar disk, while the HI gas extends even beyond the optical disk. Therefore, the HI gas is likely to be disturbed by the tidal force, and the HI linewidth is broadened.

In order to compare distances derived from the CO and HI linewidths, we measured the distances using the Tully-

Fig. 2. Histograms of W_{HI}/W_{CO} for isolated galaxies (top), weakly interacting galaxies (middle) and strongly interacting galaxies (bottom).

Table 1. Linewidths and Distances for the Interacting Galaxies

Galaxy	$W_{\text{i CO}}$ (km/s)	$W_{\text{i HI}}$ (km/s)	ΔW_i (km/s)	$W_{\text{HI}}/W_{\text{CO}}$	D_{CO} (Mpc)	D_{HI} (Mpc)	$D_{\text{HI}}/D_{\text{CO}}$	IAC
NGC 520	475	410	−65	0.863	41.9	33.6	0.86	6*
NGC 660	419	360	−59	0.859	24.0	19.2	0.86	6
NGC 772	546	602	56	1.103	30.4	35.2	1.10	3
NGC 1961	731	910	179	1.245	63.2	87.6	1.24	4
NGC 2146	531	595	64	1.121	23.1	27.3	1.12	6
NGC 2798	266	403	137	1.515	19.7	36.6	1.51	5*
NGC 3034	302	292	−10	0.967	5.5	5.2	0.97	4
NGC 3169	835	692	−143	0.829	54.1	40.8	0.82	3
NGC 3627	436	451	15	1.034	8.8	9.3	1.03	3*
NGC 3628	383	483	100	1.261	7.9	11.2	1.26	3
NGC 4038	459	602	143	1.312	18.6	27.9	1.31	5
NGC 4088	348	407	59	1.170	11.9	15.1	1.17	3
NGC 4631	307	355	48	1.156	4.1	5.1	1.16	3
NGC 5054	317	418	101	1.319	13.7	20.8	1.32	4
NGC 5194	340	626	286	1.841	4.9	12.2	1.84	4*
NGC 5713	274	370	96	1.350	13.6	21.4	1.35	3
NGC 6217	358	485	127	1.355	22.3	35.2	1.35	2

Column 1: Galaxy name. **Column 2, 3**: CO- and HI-linewidth corrected for the inclination, respectively. **Column 4**: Linewidth difference between HI and CO defined by $W_{\text{i HI}} - W_{\text{i CO}}$. **Column 5**: HI-to-CO linewidth ratio. **Column 6, 7**: Distances derived from the Tully-Fisher relation with the CO and HI linewidths, respectively. **Column 8**: HI-to-CO distance ratio. **Column 9**: Interaction class (IAC). The IAC which Dahari classified is marked with an asterisk.

Table 2. HI-to-CO Linewidth Ratio and Distance Ratio

Classification	IAC[1]	Number	$\overline{W_{\text{HI}}/W_{\text{CO}}}$	σ	$\overline{D_{\text{HI}}/D_{\text{CO}}}$	σ
Isolated Galaxies [2]	1	40	1.01	0.10	1.02	0.11
Weakly Interacting Galaxies(WIG)	2,3	8	1.16	0.16	1.25	0.26
Strongly Interacting Galaxies(SIG)	4,5	6	1.37	0.27	1.62	0.47
Mergers[3]	6	3	(0.95)	(0.12)	(0.93)	(0.18)

[1] The IAC is defined by Dahari (See Appendix).
[2] Three galaxies with CO linewidths less than 200 km s^{-1} are excluded.
[3] The number of mergers is small so that we do not discuss the statistics of mergers.

Fisher relation in B-band. We assume that the same Tully-Fisher relation is adopted for the CO and HI linewidths, because there is no significant difference between the CO and HI linewidths for the isolated galaxies and the same relationship is better to compare between them. The B-band Tully-Fisher relation which we adopted is given by Pierce & Tully (1992),

$$M_B = -7.48(\log W_i - 2.5) - 19.55, \qquad (1)$$

where M_B is the B-band absolute magnitude. In order to examine which of the linewidths is reliable for interacting galaxies, we plotted recession velocity versus distances derived from the Tully-Fisher relation with the CO and HI linewidths, and measured the Hubble constants. We compared the Hubble constants with those for the isolated galaxies. Figures 3 show the velocity-distance diagrams, namely the Hubble diagrams for interacting galaxies and isolated galaxies. The solid line and the dotted line are regression lines of the CO and HI data, respectively. The Hubble constants derived from the CO and HI linewidths for the isolated galaxies are $H_0 = 60.8 \pm 6.9$ and 60.9 ± 5.7 km s^{-1} Mpc^{-1} , respectively. The CO and HI data give a consistent value of H_0 for the isolated galaxies. Here, the errors are due to the dispersion within the sample. On the other hand, the Hubble constants derived from the CO and HI linewidths for the interacting galaxies are 65.2 ± 11.5 and 54.0 ± 9.3 km s^{-1} Mpc^{-1} , respectively. This indicates that the HI linewidths are broadened with the significance level of 89 %, and cause larger differences in H_0 estimates for the interacting galaxies.

4. Discussion and Summary

We discuss the effect of interaction on the Tully-Fisher relation. The relationship between the HI-to-CO linewidth ratio and the HI-to-CO distance ratio is given as,

(1) HI linewidths are larger than CO linewidths for interacting galaxies, and the linewidth ratio W_{HI}/W_{CO} is proportional to the strength of interaction.

(2) Distances derived from the HI Tully-Fisher relation are 25% larger for the weakly interacting galaxies and 62% larger for the strongly interacting galaxies than that derived from the CO Tully-Fisher relation.

(3) Therefore, the CO Tully-Fisher relation would give more reliable distances for interacting galaxies. This implies that the CO Tully-Fisher relation will give better distance measurement for galaxies inside rich clusters, where the tidal interaction is inevitable.

Appendix

We classified the interacting galaxies into 3 classes, WIG, SIG and mergers. The classification is based on Dahari's method (Dahari 1985). Dahari classified 167 systems of interacting and asymmetric galaxies into six groups. The IAC classifications of single- and double- galaxy systems are described in Table 3a and 3b, respectively. All galaxies in our sample are listed in the tables.

Fig. 3. Hubble diagrams for interacting galaxies (top) and isolated galaxies (bottom), radial velocities referred to the Galactic Standard of Rest (from RC3) versus distances derived from the Tully-Fisher relation. Symbols are the same as in Fig. 1. Distances derived from the CO linewidths are plotted by filled symbols and those derived from the HI linewidths are plotted by open symbols. The solid and dotted lines indicate the regression lines of the CO and HI data, respectively.

$$\frac{D_{HI}}{D_{CO}} = \left(\frac{W_{i\ HI}}{W_{i\ CO}}\right)^{k/5} \qquad (2)$$

where k is the slope of the Tully-Fisher relation ($k = 7.48$). Table 2 gives the obtained values of the ratio. In order to estimate the error, we assume that the error in the linewidths is $\pm$ 15 km s^{-1} , and the error in the slope of the Tully-Fisher relation is $\pm$ 0.50. We combine them with the dispersion of the sample. Then we find that the HI-to-CO distance ratio is 1.25 ± 0.28 for the WIG, and 1.62 ± 0.48 for the SIG. Distance derived from the HI linewidths is, thus, found to be 62% larger than that derived from the CO linewidths for SIG. When we observe distant galaxies, we may overlook tidal features, because they are faint. We suggest that the CO-line Tully-Fisher relation will be more reliable to measure the distances of galaxies for especially distant galaxies. The same should apply for galaxies in rich clusters, where galaxy-galaxy interaction is far more frequent and inevitable.

Finally we mention that the effect of interaction should be taken into account not only in the Tully-Fisher relation but also in the dynamics and evolution of spiral galaxies. The present method of the W_{CO} versus W_{HI} comparison may give a clue to reveal dynamical properties of galaxies in the era and regions where galaxy-galaxy interaction would have a significant effect.

We summarize our results as follows:

Table 3a. Definition of Interacting Class (IAC) of Single Galaxies

IAC	Description	Galaxy NGC
1	Symmetric (isolated)	
2	Slightly asymmetric, diffuse extensions	6217
3	Asymmetric, extended arms	4088
4	Distorted, out of shape	1961
5	Strongly disordered	–
6	Aftermath	660,2146

Table 3b. Definition of Interaction Class(IAC) for Pair Galaxies

	Companion Size					
	Same		$\sim 1/2$		Small	
Separation	IAC	NGC	IAC	NGC	IAC	NGC
Large, no contact	3	3169	2	–	1	–
		3627*				
		3628				
		5713				
Large, connected	4	3034	3	–	2	–
Small, no contact	4	–	4	–	3	772
						4631
Small, connected	5	2798*	4	5194*	4	5054
		4038				
Overlap	6	520*	5	–	4	–

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